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Evaluation of Butanol–Gasoline Blends in a Port Fuel-injection, Spark-Ignition Engine

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Résumé — Évaluation de mélange butanol-essence dans un moteur à allumage commandé à injection indirecte — Cet article évalue le potentiel de l'utilisation de différents mélanges butanol-essence dans un moteur à allumage commandé à injection indirecte afin de quantifier l'influence de l'ajout de butanol sur les émissions des hydrocarbures imbrûlés (HC), le monoxyde de carbone (CO) et les oxydes d'azote (NOx). De plus, l'influence sur la stabilité de combustion, le délai d'inflammation et sur la durée de la phase de combustion turbulente développée y sont également présentés. Les principaux résultats : 1) un mélange de 40 % butanol et 60 % essence (B40) par volume diminue les émissions de HC ; 2) aucun effet significatif sur les émissions de NOx n'a été observé à l'exception du mélange 80 % butanol/20 % essence ; 3) l'ajout de butanol améliore la stabilité de combustion ; 4) l'ajout de butanol réduit le délai d'inflammation, quantifié par la durée pour consommer 10 % de masse de gaz frais; et 5) la consommation spécifique de carburant pour un mélange stoechiométrique de B40 est 10 % supérieure à celle de l'essence.

Abstract — Evaluation of Butanol–Gasoline Blends in a Port Fuel-Injection, Spark-Ignition Engine *— This paper assesses different butanol–gasoline blends used in a port fuel-injection, spark-ignition engine to quantify the influence of butanol addition on the emission of unburned hydrocarbons, carbon monoxide, and nitrogen oxide. Furthermore, in-cylinder pressure was measured to quantify combustion stability and to compare the ignition delay and fully developed turbulent combustion phases as given by 0%–10% and 10%–90% Mass Fraction Burned (MFB). The main findings are: 1) a 40% butanol/60% gasoline blend by volume (B40) minimizes HC emissions; 2) no significant change in NOx emissions were observed, with the exception of the 80% butanol/20% gasoline blend; 3) the addition of butanol improves combustion stability as measured by the COV of IMEP; 4) butanol added to gasoline reduces ignition delay (0%–10% MFB); and 5) the specific fuel consumption of B40 blend is within 10% of that of pure gasoline for stoichiometric mixture.*

INTRODUCTION

Adding alcohol to conventional hydrocarbon fuels for use in a spark-ignition engine occasions a small increase in fuel octane rating, which can be used to slightly increase the compression ratio. Alcohol addition, however, can increase power for a given engine displacement and compression ratio, thereby reducing fossil-fuel consumption and CO_2 emissions [1-3]. Ethanol and butanol are two alcohols or oxygenated fuels that can be blended with gasoline to reduce fossil-fuel consumption and are often associated with a possible decrease in pollutant emissions. Since ethanol use for spark-ignition engines has been much more studied than butanol, we begin by reviewing the main findings associated with ethanol–gasoline blends. This provides a benchmark against which butanol–gasoline blends and other oxygenated fuels can be evaluated.

Specific Fuel Consumption (SFC) is directly linked to the stoichiometric air-to-fuel ratio and provides a comparison of mass consumed per unit of power delivered. The SFC of different ethanol–gasoline blends was measured in [4, 5] and showed that the SFC increased with the presence of ethanol in gasoline. For E10 (10% ethanol and 90% gasoline), E30, and E100, an increase of 4%, 12%, and 59% in SFC, respectively, were reported by [4], while [5] reported a nearly constant 20% increase of SFC over different engine speeds at full load for E50 and a low compression ratio engine. A commercial 4-cylinder engine fed with different blends lower than E30 at different engine speeds and loads was used by [6], who found no significant change in SFC as the engine was run leaner as the concentration of ethanol increased.

As for Unburned HydroCarbon (UHC) emissions, the experiments themselves impact on the potential gains associated with ethanol use. Different ethanol–gasoline blends were evaluated in [5] with a low compression ratio of 6 at full load and low engine speed. They found that E50 minimized UHC with a 25% reduction as compared to gasoline. Further increases in ethanol concentration were associated with UHC emissions increasing by more than 50% for E100. In [7], however, UHC emissions were reported for different ethanol–gasoline blends and engine speeds, but no general trends could be found between ethanol concentration and UHC emissions. Hsieh *et al*. [6] also reported a decrease in UHC emissions, but the reduction can be partially attributed to a decreased equivalence ratio with the increased ethanol content. A small motorcycle engine was used to compare pure gasoline to E10 in [8] at different engine conditions between idle and a load representative of a motorcycle operating at 50 km/h. UHC emissions were reported to be reduced by around 40% with E10 at idle and a load equivalent to 50 km/h, while no significant change was observed for conditions in between. In [9], UHC emissions were reduced by 15% and combustion cyclic variability were minimized with E10 on a carbureted spark-ignition engine.

Finally, ethanol's potential for influencing nitrogen-oxide (NOx) emissions was evaluated in [5], which reported that NOx emissions decreased as the ethanol concentration increased. On the other hand, NOx emissions were higher for E30 than for gasoline in [6], when both mixtures were at stoichiometry. In [8], no significant change in NOx emissions was reported as the engine load increased when E10 was used. On the other hand, [10] reported a decrease and an increase in NOx emissions depending on the engine speed and load for an engine fueled with E10. It was suggested in [11] that the decrease of NOx emissions was linked to the higher vaporization heat of ethanol, which reduced the in-cylinder mixture temperature. In light of the above results, however, this explanation still needs to be validated.

On the other hand, butanol's potential remained to be determined, since very few studies have been performed on butanol-fueled engines or even butanol combustion. Nevertheless, butanol is promising, since its properties are closer to gasoline than ethanol, which is widely used as an additive and blending agent. One advantage of butanol over ethanol is that it is much less anhydrous, which greatly reduces the risk of water contamination/absorption by the fuel. Alasfour [12-14] is among the few who have studied butanol–gasoline blends. In [12], a single-cylinder engine was used to measure engine efficiency at different equivalence ratios with a 30% butanol–gasoline blend. The results showed a 7% decrease of power when compared to the same engine fueled with pure gasoline.

In another study [13], NOx emissions were reported as a function of equivalence ratio. The result showed a decrease in NOx emissions for equivalence ratios between 0.9 and 1.05 when a 30% butanol–gasoline blend was used. More specifically, a 9% decrease in NOx emissions was reported when peak emissions were compared. Peak NOx emissions were found at a slightly leaner mixture for a 30% butanol–gasoline blend than for pure gasoline. Finally, in [14], the influence of spark timing on NOx emissions was presented for the 30% butanol–gasoline blend only. As expected, an increase in spark timing was associated with an increase in NOx emissions.

This paper presents NOx, CO, and UHC emissions for different butanol–gasoline blends to assess the influence of butanol addition to gasoline in a port fuel-injection, spark-ignition engine. Furthermore, combustion characterization from in-cylinder pressure measurements is also presented to quantify the changes associated with butanol addition. This paper is divided as follows. First, the experimental set-up is briefly presented. Second, the influence of butanol addition on pollutant emissions is presented and discussed, followed by in-cylinder pressure measurement and the associated diagnostics. Finally, the paper finished by restating the main findings.

1 EXPERIMENTAL SET-UP

Experiments were conducted with a 4-cylinder, 16-valve, 1.6-L spark-ignition Honda engine, model D16Z6, with a

compression ratio of 9.6. The engine was connected to an eddy current dynamometer and associated controller. The experimental results presented herein were obtained with a fully warmed engine and calibrated exhaust gas analyzers according to manufacturer procedures. The engine operating conditions, unless specified otherwise, were an engine speed of 2000 RPM and a Break Mean Effective Pressure (BMEP) of 262 kPa, which corresponds to an Indicated Mean Effective Pressure (IMEP) of 3.2 bars and can be considered as representative of highway driving.

The engine was fueled with different butanol–gasoline blends at different engine loads, spark timings, and equivalence ratios. Only representative results are presented herein. The experiments were conducted with summer gasoline as found at the pump in Canada and n-butanol with a purity of 99.99%. butanol–gasoline blends are reported by volume with the following blends being studied: B0, B20, B40, B60, and B80. Finally, Table 1 presents the respective properties of gasoline, ethanol, and butanol for fuel comparison.

TABLE 1
Fuel properties

	Gasoline	Butanol	Ethanol
Chemical formula	~$C_8H_{15.6}$	$C_4H_{10}O$	C_2H_6O
Low heating value (MJ/kg)	43.5	32	26.8
Latent heat of vaporization (kJ/L)	223	474	725.4
RVP (kPa)	60-90	18.6	19.3
A/*F* stoichiometric	14.6	11	9
Density (kg/m^3)	720-775	813	794
Oxygen (% weight)	< 2.7	21.6	34.7
RON	95	113	111
Adiabatic flame temperature (K)	2370	2340	2310

The excess air ratio was measured with a Bosch wideband exhaust-gas oxygen sensor, while minimum advance for best torque (MBT) was used, unless otherwise specified. Unburned HydroCarbon (UHC) was measured with a Heated Flame Ionization Detector (HFID), while nitrogen oxide (NOx) was measured with a Heated ChemiLuminescent Detector (HCLD). Carbon monoxide (CO) and carbon dioxide (CO_2) were measured with non-dispersive infrared analyzers (NDIRs); oxygen (O_2) was measured with a galvanic fuel cell, used to validate the wide-band oxygen sensor measurements which can be influenced by the type of fuel and especially when alcohol-based fuel is used. Analyzer specifications are presented in Table 2. Exhaust-gas samples were first cooled with an ice bath to prevent water condensation in the analyzers.

Relative emission used throughout this paper to allow comparison with results reported by others and is defined by Equation (1):

$$RE_x = \frac{E_b - E_g}{E_g} \quad (1)$$

TABLE 2
Specification of the analyzers

	Range	Accuracy
CO	0%-10%	0.01%
O_2	0%-25%	0.25%
NO/NO_x	0-6000 ppm	10 ppb
HC (CH_4)	0-4000 ppm	10 ppb
CO_2	0%-20%	0.1%

where RE_x is the relative emission of pollutant x, while E_b and E_g are the measured emissions of pollutant x when the engine is fueled with a butanol–gasoline blend and pure gasoline, respectively.

In-cylinder pressure measurements were acquired with a Kistler pressure transducer embedded in a spark plug. For each measurement, 250 cycles were acquired based on a 1000 pulse/rotation optical encoder with a LabVIEW acquisition-system developed in-house. An in-house MATLAB program was used for postprocessing of the in-cylinder pressure. To quantify the variability of indicated work per cycle, the Coefficient Of Variation of Indicated Mean Effective Pressure (COV of IMEP) was calculated as defined by Equation (2):

$$COV_{IMEP} = \frac{\sigma_{IMEP}}{\overline{IMEP}} \quad (2)$$

where σ_{IMEP} is the standard deviation in IMEP and $\overline{IMEP}$ is the mean IMEP, taken over 250 cycles. The IMEP was calculated by the integration of PdV over a cycle divided by the displacement volume of the cylinder. The Mass Fraction Burned (MFB) was computed from Rassweiler and Withdrow method [15]. The specific heat at constant pressure of the gaseous phase of gasoline and butanol necessary to calculate the MFB and the heat release were taken from [16] and [17], respectively.

2 RESULTS AND DISCUSSION

2.1 Unburned Hydrocarbon Emissions

The UHC emissions are presented first since they hint at the quality or change in the combustion process when butanol is added to gasoline. Figure 1 shows the influence of equivalence ratio for different butanol–gasoline blends. Blends with 40% butanol or less display similar HC emissions than gasoline. However, it was possible to operate the engine with a slightly leaner mixture with B40, compared to the leanest gasoline mixture.

For a stoichiometric mixture, B0, B20 and B40 all yielded similar UHC emissions. Further increasing the butanol content brings the emission levels above to that of gasoline with an 18% increase in the case of B60, while B80 shows a

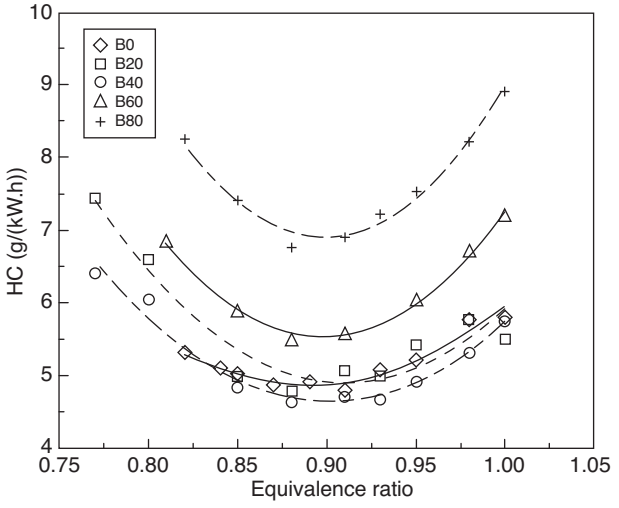

Figure 1

Influence of equivalence ratio on UHC for different butanol blends.

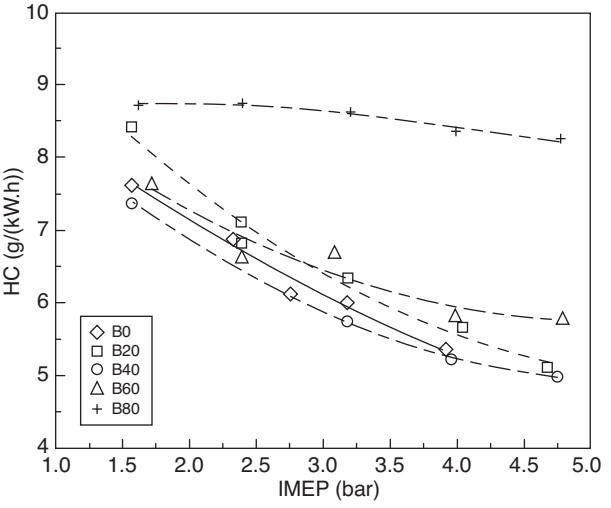

Figure 2

HC emissions as a function of engine load for different butanol blends at 2000 RPM and stoichiometric mixture.

47% increase of UHC emissions compared to gasoline. The relative reduction of UHC emissions obtained with B20 and B40 (less than 5%) are lower than those results from [18] with the 30% ethanol–gasoline (E30) blend at a similar load and same engine speed that yield a 20% reduction in relative UHC with a stoichiometric mixture.

The influence of load with a stoichiometric mixture was also verified by evaluating engine performance at IMEP of 160, 240, 320, 400, and 470 kPa for all butanol–gasoline blends, as presented in Figure 2. As can be seen, increased load results in a slight decreased UHC for all blends, B80 having the highest UHC emissions by far at all loads. This decrease in UHC emissions with increasing load agrees with the results of [19] obtained with pure ethanol, but contradicts the trend observed in [18], in which UHC emissions slightly increased with load both with pure gasoline and E30.

2.2 Carbon-monoxide Emissions

Figure 3 presents carbon-monoxide (CO) emissions as a function of equivalence ratio for the different blends studied. It is observed that, for a stoichiometric mixture, B20, B40, and B60 offer lower CO emissions than pure gasoline. B80, on the other hand, produces the same level of CO emissions as gasoline for stoichiometric mixtures and produces the highest emission levels at all other equivalence ratios tested during our experiment. For lean mixtures, CO emissions generally increase as does the butanol concentration, suggesting that complete CO oxidation is more difficult with butanol fuel. However, it is also observed that for a given butanol concentration, the CO emissions are relatively constant for lean mixtures. This behaviour of CO is due to the fact that the equivalence ratio controls CO emissions until lean mixture are reached after what CO emissions do not vary significantly [20]. These low CO emissions under lean mixtures might be explained by the fact that if the hydrocarbon can start oxidising, then there is more than enough oxygen available to carry on the oxidation process. On the other hand, HC emissions increase for lean mixture because of incomplete combustion as the combustion quality deteriorates [20]. This combustion deterioration for lean mixture could be associated to the increase inhomogeneity of the mixture that translated into non-flammable pockets of too lean mixture which becomes responsible for the increase of HC emissions.

2.3 Nitrogen Oxide

Figure 4 shows the variation of NOx emissions according to the butanol content of the gasoline. When the concentration is less than 60%, there is no significant change in NOx emissions for stoichiometric mixtures. A slight decrease of NOx emissions, however, can be observed when the mixture's equivalence ratio is less than or equal to 0.85 for blends with a butanol concentration higher than 40%. On the other hand, B80 offers a noticeable difference in NOx emissions for all equivalence ratios. This can be linked to the incomplete combustion as measured by the increase in UHC emissions presented in Figure 1. These higher UHC emissions for B80 resulted in a lower heat release and, therefore, lower temperature.

It is worth noting that the trend of NOx emissions as a function of equivalence ratio for each blend presented in Figure 4 is similar to the results with a single-cylinder engine

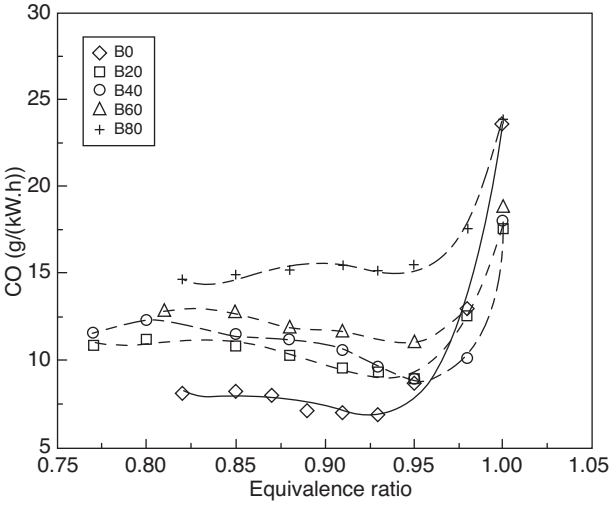

Figure 3

Carbon-monoxide emissions as a function of equivalence ratio and blends.

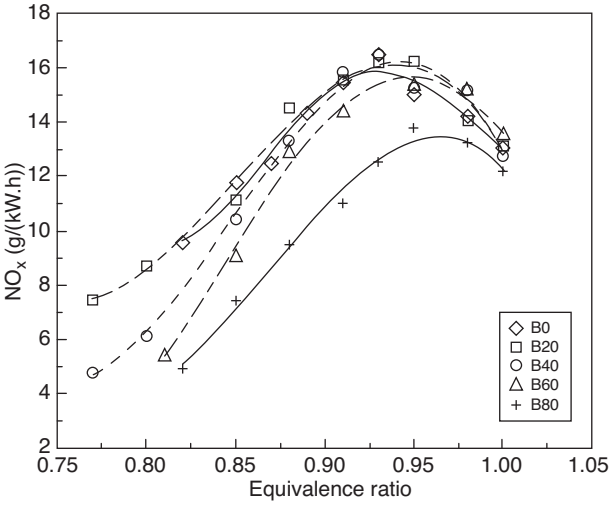

Figure 4

Influence of butanol addition and equivalence ratio on specific NOx emissions.

reported in [13]. The results in [13] show a decrease of approximately 10% of peak NOx emissions for B30 in comparison to gasoline. Furthermore, [13] reported a shift of peak emissions to a slightly leaner mixture when B30 was compared to gasoline. Analysis of the results in [13], however, reveals that the shift in peak NOx emissions results from an equivalence ratio of 0.95 for gasoline to 0.9 for B30. This is similar to the results in Figure 3, which shows that peak NOx emissions occurs at an equivalence ratio between 0.93 and 0.95 for all blends. The main difference between the results herein and that in [13] concerns the reduction of NOx emissions near the point of stoichiometry. Our results show very little difference (around 7%) in NOx emissions at an equivalence ratio of 1, while [13] reported a 50% reduction of NOx emissions for the same equivalence ratio. The small difference in NOx emissions observed in Figure 4 at stoichiometry for butanol blends is nevertheless comparable to the results in [18] with E30, which show a slight 10% decrease in NOx emissions at the same engine speed and for a similar load as the results in Figure 4.

NOx emissions for a stoichiometric mixture at different engine loads were also evaluated. All butanol blends therein follow the same trend as the results with pure gasoline and NOx emissions are within 10% to that for gasoline. Comparable changes in NOx emissions were reported by [18] as a function of engine loads with E30. Other researchers such as [6], however, have reported no clear trend in NOx emissions with increasing ethanol blends; a major decrease in the pollutant was observed, depending on ethanol–gasoline blend and engine load. They concluded that the level of NOx emissions was more related to engine load than to fuel ethanol content.

2.4 Specific Fuel Consumption

One of the advantages of butanol over ethanol as an alternative fuel is its higher air-to-fuel ratio for stoichiometric mixtures and its slightly higher Combustion Enthalpy (CE), which should translate into a lower increase in specific fuel consumption compared to ethanol. As expected, the SFC increases as the butanol content is increased, with the highest increase observed with B80 (28% increase in SFC for a stoichiometric mixture in *Tab. 3*). The increase in SFC in Table 3 shows that butanol blends perform better when compared to an increase in SFC of 59% [4] with pure ethanol, 19% [5] with E50, and around 27% [7] with E60. The relative low increase in specific fuel consumption associated with butanol blends can be linked to the higher combustion enthalpy of the fuel, which is also presented in Table 3. For B20, a 5% change in Combustion Enthalpy compared to gasoline results in a 5% change in SFC.

Table 4 presents the influence of engine load on the relative SFC at different engine loads and for butanol blends at a slightly lean mixture (0.87 equivalence ratio). It is observed that, for a given blend, the increase in SFC is relatively constant as the load increases. This trend is similar to the results in [18] with ethanol, which show that the SFC for E30 at a constant engine speed and slightly greater loads increased by 5% to 8%, depending on the load.

2.5 In-cylinder Pressure Measurements

In-cylinder pressure measurements are presented to compare the difference in cyclic variability of combustion and to quantify the difference in combustion phasing, such as

TABLE 3

Relative SFC and change in LHV as a function of butanol addition at 2000 RPM and IMEP 367 kPa

Blend	Relative SFC			Change in
	Φ = 0.83	Φ = 0.91	Φ = 1.0	CE (%)
B20	+7.4	+6.4	+1.8	–5.0
B40	+10.8	+11.6	+9.4	–9.8
B60	+18.6	+17.9	+18.1	–14.5
B80	+26.8	+25.2	+27.7	–19.0

TABLE 4

Relative SFC as a function of load for an equivalence ratio of 0.87 and engine speed of 2000 RPM

IMEP (bar)	B20	B40	B60	B80
1.6	5.7%	8.5%	14.3%	17.9%
2.4	5.6%	10.6%	19.1%	26.8%
3.2	6.5%	10.6%	13.5%	22.7%
4.0	5.2%	9.0%	15.2%	23.7%
4.7	5.7%	8.1%	14.5%	23.9%

ignition delay, given by 0%-10% MFB, and the fully developed combustion phase, given by 10%-90% MFB. Figure 5 shows that butanol addition improves combustion stability by reducing the Coefficient Of Variation of Indicated Mean Effective Pressure (COV of IMEP). In fact, the improvement seems to be independent of butanol concentration, particularly near the stoichiometry, since the benefit of adding 20% butanol to gasoline is quite similar to adding 40%, 60%, or 80%. These results differ from [9], which reported that adding 10% of ethanol minimized the COV of IMEP and that a further increase in ethanol concentration resulted in an increase of combustion variability such that the use of E20 resulted in a higher COV of IMEP than pure gasoline.

The difference in the ignition delay, as characterized by the 0%-10% MFB, shows a slight decrease in duration as butanol is added for a stoichiometric mixture, as illustrated in Figure 6. This shorter ignition delay observed in the 0%-10% MFB is consistent with shock tube experiments conducted with butanol [21] and gasoline [22]. The ignition delay reported at 1 atmosphere and a temperature of 1615 K is 0.06 ms for butanol [21] and 0.2 ms for the gasoline surrogate fuel [22].

The difference in the main combustion duration, as expressed by the 10%-90% MFB, was also calculated for all blends. A 3 to 5 Crank-Angle Degrees (CADs) variation is observed with respect to pure gasoline suggesting that the addition of butanol yields a slight difference in burning speeds.

This slight difference in ignition delay and main combustion duration is also reflected in the minimum advance for best torque spark timing, which was found to be retarded by 2 or 3 CADs for the butanol blend compared to gasoline. This finding is similar to the results in [7] for ethanol–gasoline blends, but it differs from the increase of 5 to 15 CADs in spark timing reported in [19] for E100.

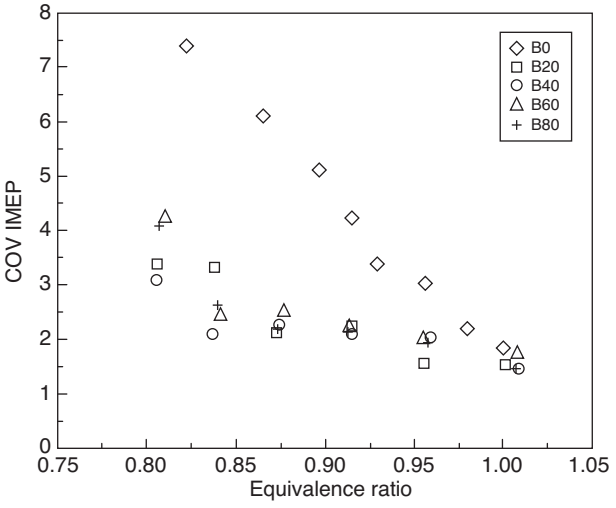

Figure 5

COV of IMEP as a function of equivalence ratio and different butanol concentrations.

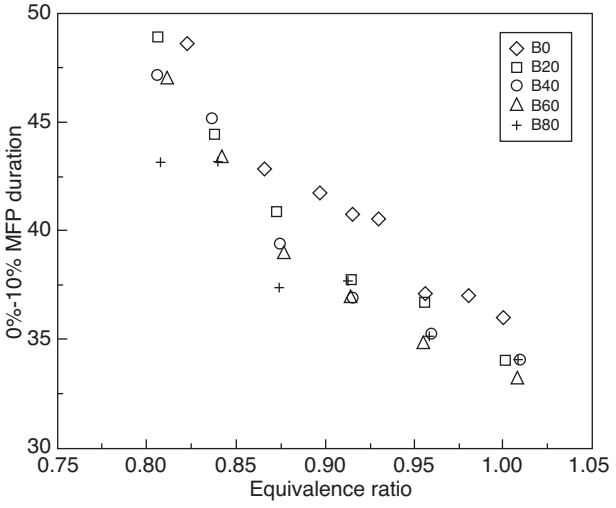

Figure 6

Combustion delay of butanol blends as a function of equivalence ratio.

CONCLUSION

Different butanol–gasoline blends were tested in a port fuel-injection, spark-ignition engine that was instrumented to measure in-cylinder pressure, while pollutant emissions were measured at the exhaust pipe. It is observed that, for the

engine used herein, an optimum concentration of 40% butanol in gasoline enables to run the engine at leaner mixture than gasoline. However, B20 and B40 offered similar UHC emissions than gasoline and that UHC emissions increased at higher butanol concentrations. Blends B60 and B80 produced higher UHC levels than pure gasoline. For stoichiometric and slightly lean mixtures, NOx emissions levels were similar for all blends, except B80, which evidenced lower emission levels due to combustion deterioration (higher UHC levels). It was possible to obtain stable engine operation with leaner mixtures with B20 and B40, which decreased the NOx emissions to a lower level than with pure gasoline at its leanest mixture.

The slight increase in SFC with the butanol addition was related to the blend's reduced combustion enthalpy. For example, B40 has a 10% lower combustion enthalpy than gasoline, which results increases SFC by 10% for stoichiometric and slightly lean mixtures. As for engine load, B20 and B40 yielded trends similar to gasoline with respect to UHCs and NOx emissions, while B60 and B80 generated smaller decreases in UHC according to engine load, which suggests, as UHC emissions have shown, a decrease in the completeness of combustion.

Finally, it can be inferred from in-cylinder pressure measurement that adding butanol, even in small concentrations, reduces the COV of IMEP, thereby stabilizing combustion, particularly with lean mixtures. Analyzing in-cylinder pressure measurement has shown that butanol addition, even in small concentrations, reduced ignition delay by 2 CADs to 3 CADs and that the fully turbulent combustion phase (10%-90% MFB) was similar in duration for all blends and pure gasoline. This latter finding suggests that gasoline and butanol have a similar laminar flame speed.

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